

CONDITIONED REINFORCEMENT VALUE AND CHOICE

RAY A. PRESTON AND EDMUND FANTINO

UNIVERSITY OF CALIFORNIA-SAN DIEGO

The delay-reduction hypothesis of conditioned reinforcement states that the reinforcing value of a food-associated stimulus is determined by the delay to primary reinforcement signaled by the onset of the stimulus relative to the average delay to primary reinforcement in the conditioning situation. In contrast, most contemporary models of conditioned reinforcement strength posit that the reinforcing strength of a stimulus is some simple function only of the delay to primary reinforcement in the presence of stimulus. The delay-reduction hypothesis diverges from other conditioned reinforcement models in that it predicts that a fixed-duration food-paired stimulus will have different reinforcing values depending on the frequency of its presentation. In Experiment 1, pigeons' key pecks were reinforced according to concurrent-chains schedules with variable-interval 10-second and variable-interval 20-second terminal-link schedules. The initial-link schedule preceding the shorter terminal link was always variable-interval 60 seconds, and the initial-link schedule requirement preceding the longer terminal link was varied between 1 second and 60 seconds across conditions. In Experiment 2, the initial-link schedule preceding the longer of two terminal links was varied for each of three groups of pigeons. The terminal links of the concurrent chains for the three groups were variable-interval 10 seconds and 20 seconds, variable-interval 10 seconds and 30 seconds, and variable-interval 30 seconds and 50 seconds. In both experiments, preference for the shorter terminal link was either a bitonic function or an inverse function of the initial-link schedule preceding the longer terminal-link schedule. Consistent with the predictions of the delay-reduction hypothesis, the relative values of the terminal-link stimuli changed as a function of the overall frequency of primary reinforcement. Vaughan's (1985) melioration model, which was shown to be formally similar to Squires and Fantino's (1971) delay-reduction model, can be modified so as to predict these results without changing its underlying assumptions.

Key words: choice, conditioned reinforcement, delay-reduction hypothesis, incentive theory, melioration, concurrent chains, key peck, pigeons

Recent reviews of conditioned reinforcement models have reflected a growing dissatisfaction with the large number of competing models sharing little in their theoretical bases yet apparently indistinguishable in their ability to account for basic phenomena. Davison (1987) compared the ability of three contemporary models (Davison & Temple, 1973; Killeen, 1982; Squires & Fantino, 1971) to account for more than 10 concurrent-chains studies and concluded that there was no basis for choosing one over the others. Each model predicted some sets of data better, and some worse, than the

other models. Davison concluded that quantitative models were premature and that model building should be forsworn in favor of a more thorough experimental analysis. Williams (1988) also wondered at the implications of so many models of concurrent-chains performance but suggested that the situations they address may be so complicated as to provide no alternative. Part of the difficulty may lie in the practice of comparing overall preference measures with the overall predictions of the models without consideration of the separate individual assumptions underlying the molar predictions of each model. The present paper addresses the basic differences among several models' assumptions about the determinants of the reinforcing value of the terminal links of concurrent chains and suggests that some models fundamentally misconceive the determinants of conditioned reinforcement strength.

Models of Conditioned Reinforcement

The delay-reduction hypothesis. The delay-reduction hypothesis was first developed (Fan-

This report is based on a dissertation submitted by Ray A. Preston to the University of California-San Diego in partial fulfillment of requirements for the degree of Doctor of Philosophy. Research was supported by NIMH Grant MH-20752 and NSF Grant BNS 83-02963 to the University of California-San Diego. Reprints may be obtained from Ray A. Preston, Environmental Health Sciences Center, University of Rochester Medical Center, Rochester, New York 14642, or from Edmund Fantino, Department of Psychology C-009, University of California-San Diego, La Jolla, California 92093-0109.

tino, 1969b) to account for choice in a two-alternative concurrent-chains procedure. (See Experiment 1, General Procedure, for a complete description of the concurrent-chains procedure.) Like Herrnstein (1964), Fantino assumed that relative response rates in the initial links of a concurrent-chains schedule would match the relative values of the terminal-link stimuli but proposed that the effects of the temporal delays in the terminal links had to be considered within the overall temporal context in which they were embedded. The delay-reduction hypothesis states that the effectiveness of a stimulus as a conditioned reinforcer is best predicted by the reduction in time to primary reinforcement signaled by the onset of the stimulus relative to the average time to reinforcement in the conditioning situation (Fantino, 1969b; Fantino & Davison, 1983; Squires & Fantino, 1971). For example, in a simple chain schedule, the conditioned-reinforcing strength of a stimulus associated with a fixed-interval (FI) 10-s terminal link would be greater if it followed an FI 90-s initial link than if it followed an FI 10-s initial link. According to the delay-reduction hypothesis, this is because in the first case the onset of the terminal-link stimulus signals that 90% of the overall 100-s delay to food has elapsed (i.e., a delay reduction of 90% relative to the average expected delay to reinforcement). In the second case, the same-duration stimulus signals a delay reduction of only 50% because 10 s are left of the overall wait of 20 s per reinforcer.

Specifically, Fantino (1969b) proposed that

$$\frac{B_L}{B_R} = \frac{T - t_{2L}}{T - t_{2R}}, \quad (1)$$

where B_L and B_R represent the initial-link responses on the left and right chains, t_{2L} and t_{2R} represent the average delays to reinforcement in the two terminal links, and T is the average time to reinforcement in the conditioning situation, usually measured from the onset of the initial links in a concurrent-chains procedure:

$$T = \frac{1}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} + \frac{\frac{1}{t_{1L}}}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} \cdot t_{2L} + \frac{\frac{1}{t_{1R}}}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} \cdot t_{2R}.$$

Fantino (1969a) showed the superiority of the delay-reduction hypothesis over simple match-

ing to terminal-link reinforcement immediacies (Herrnstein, 1964) by comparing preference for terminal links of variable-interval (VI) 30-s and VI 90-s schedules under a range of values of T . Contrary to the simple matching view, Fantino (1969a) predicted that increasing the initial-link delays would decrease preference for the VI 30-s terminal link through its effect on the average delay to food (i.e., T). Preference for the shorter terminal link decreased as the equal initial-link schedules increased.

One limitation of Fantino's (1969b) original model was that it did not account for preference in concurrent-chains schedules when the initial links were unequal. For instance, the model predicted indifference for equal terminal links even when the initial-link schedules were greatly disparate. Squires and Fantino (1971) and Fantino and Davison (1983) subsequently modified the model to account for this situation. According to Squires and Fantino (1971),

$$\frac{B_L}{B_R} = \frac{r_L}{r_R} \cdot \frac{T - t_{2L}}{T - t_{2R}}, \quad (2)$$

where the additional terms, r_L and r_R , represent the average rates of reinforcement on the left and right chains (i.e., the inverse of the sum of the average initial- and terminal-link durations on each chain). Preference is thus predicted to be a joint function of the ratio of the values of the conditioned reinforcement provided by the terminal-link stimuli ($(T - t_{2L})/(T - t_{2R})$) and the ratio of the rates of primary reinforcement on the two keys (r_L/r_R).

Other accounts of conditioned reinforcement (Davison, 1987; Davison & Temple, 1973; Killeen, 1982; Vaughan, 1985) have not explicitly incorporated a role for the context of reinforcement (i.e., T) in determining conditioned reinforcement value but still have been quite successful in accounting for a variety of conditioned reinforcement phenomena. However, like Squires and Fantino (1971), each of the extant concurrent-chains models assumes that preference is determined not only by the values of the conditioned reinforcers but also by the rates of primary or conditioned reinforcement. As will be shown, the interaction between the purported determinants is often such that the role of the context in determining conditioned reinforcement value is obscured.

Incentive theory. Killeen (1982) predicted that the relative rates of concurrent-chains initial-link responses will match the relative strengths of the two chain schedules, with the amount of behavior determined by the rate of reinforcement on each key. The strength (S) of a schedule is a combination of three factors: the rate of primary reinforcement (r_L , if for the left key), the primary (P) effect of the reinforcer, and any conditioned reinforcement (C). Specifically,

$$S = r_L(S_d) = r_L(P + C)$$

where S_d equals the sum of the directive (P and C) effects of the schedule. The primary effects of the reinforcer are decayed exponentially by any delay imposed between a given response (e.g., an initial-link response producing a terminal link) and a reinforcer such that

$$P = e^{-q \cdot t_{2L}}$$

where q is a rate constant and t_{2L} is the delay between the response and the reinforcer. When there is no delay, $P = 1$. As applied to the concurrent-chains procedure, t_{2L} is equal to the duration of the terminal link of the chain because the primary reinforcer is delayed from the initial-link response by that duration. As such, the primary reinforcer's effect upon initial-link responses is degraded. The conditioned reinforcement contingent upon initial-link responding is usually immediate, and therefore its effect is not decayed. However, because conditioned reinforcers are not as effective as primary reinforcers, the strength of the conditioned reinforcer is predicted to be equal to the immediacy of primary reinforcement such that

$$C = \frac{1}{t_{2L}}.$$

Again, the rate of primary reinforcement on a key is

$$r_L = \frac{1}{t_{1L} + t_{2L}}.$$

The complete model, then, predicts that

$$\frac{B_L}{B_R} = \frac{r_L}{r_R} \cdot \frac{e^{-q \cdot t_{2L}} + \frac{1}{t_{2L}}}{e^{-q \cdot t_{2R}} + \frac{1}{t_{2R}}}. \quad (3)$$

As in the delay-reduction hypothesis, prefer-

ence is predicted to be a joint function of two variables. These are the ratio of the reinforcing values of the terminal-links ($(e^{-q \cdot t_{2L}} + 1/t_{2L}) / (e^{-q \cdot t_{2R}} + 1/t_{2R})$) and the ratio of the rates of primary reinforcement on the two keys (r_L / r_R). Unlike the delay-reduction hypothesis, which predicts that the effects of the terminal-link schedules will be affected by the overall temporal delay (i.e., T), incentive theory assumes the directive effects to be determined solely by the terminal-link schedules. Killeen and Fantino (1990) showed that incentive theory and delay reduction may be indistinguishable at a molar level depending upon as-of-yet untested revisions in the assumptions of incentive theory. Should experiments support their hypotheses, incentive theory and delay reduction would differ with respect to the mechanisms purported to underlie the model of Squires and Fantino (1971) but not at the level of overall predictions of preference.

Melioration theory. Vaughan (1982, 1985) proposed a choice model based largely on the classical conditioning model of Rescorla and Wagner (1972). According to melioration theory, the distribution of time spent (and consequently, responses emitted) in the two initial links is determined by the local rates and values of reinforcement on each of the two alternatives. For instance, the left initial-link stimulus has a value (V_{1L}) that is a negatively accelerated function of the local rate of reinforcement (r_{1L} , defined as the reinforcers on the left divided by the time spent actually responding on the left) approaching asymptote at high rates of reinforcement. The asymptote is the value of the reinforcer contingent upon initial-link responding or, in a chain schedule, the value of the terminal-link stimulus at the moment of its presentation. The value of the terminal-link stimulus is similarly determined by the local rate of reinforcement (i.e., food presentation) in its presence. Thus, the value of the left initial-link stimulus is a simple hyperbolic function of the value and frequency of V_{2L} :

$$V_{1L} = \frac{r_{1L}}{r_{1L} + a} \cdot V_{2L},$$

where a is a parameter (scaled in reinforcements per unit time) that limits the rate of growth of V_{1L} and

$$V_{2L} = \frac{r_{2L}}{r_{2L} + a} \cdot V_{3L}.$$

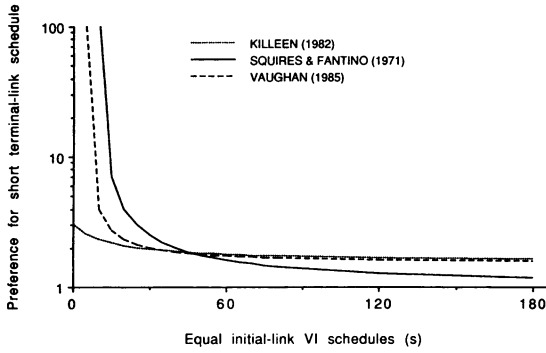


Fig. 1. Predicted preference as a function of the absolute schedule values in the initial links of a concurrent-chains procedure. Shown are the predictions of Killeen (1982), Squires and Fantino (1971), and Vaughan (1985) for a concurrent-chains procedure with VI 10-s and VI 20-s terminal links. Preference for the shorter terminal link is plotted on the ordinate.

V_{3L} is the value of the primary reinforcement contingent upon terminal-link responses. For equal amount and kind of food on the left and right keys, the value of the primary reinforcer can arbitrarily be assigned a fixed value, say 5.0.

It is not an axiom of melioration theory that response allocation will necessarily match the relative strengths of the choice schedules. Instead, response allocation is determined by the local rates and values of reinforcement in the two initial links. When the value (e.g., V_{1L}) of one initial-link stimulus is higher than the value of the other, more time will be spent on the higher valued key. This, in turn, decreases the value on that key. This process (melioration) will continue until the initial-link values on the two keys are equal. Thus, melioration results finally in a response distribution that makes $V_{1L} = V_{1R}$. Preference can be predicted by setting $V_{1L} = V_{1R}$ and solving for the proportion of initial-link times (see Vaughan, 1985, Appendix 3), resulting in:

$$\frac{B_L}{B_L + B_R} = \frac{r_L r_R (V_{2L} - V_{2R}) + a r_L V_{2L}}{a (r_L V_{2L} + r_R V_{2R})}. \quad (4)$$

This is equivalent (see Appendix 1) to the corresponding ratio form of the model,

$$\frac{B_L}{B_R} = \frac{V_{2L} - V_{2R} + a t_{1R} V_{2L}}{V_{2R} - V_{2L} + a t_{1L} V_{2R}}, \quad (5)$$

where t_{1L} and t_{1R} have the same meanings as in Squires and Fantino (1971). Vaughan

(1985) commented that the predictions of melioration and the delay-reduction hypothesis were very similar for a wide range of concurrent-chains conditions, and Luco (1990) showed that a variant of the delay-reduction hypothesis could be derived from the general assumptions of the process of melioration. Vaughan's specific formulation can also be shown to roughly equal the delay-reduction hypothesis. The ratio form of Vaughan's (1985) model can be expressed as

$$\frac{B_L}{B_R} = \frac{\frac{1}{t_{1L}} \cdot T_L - V_{2R}}{\frac{1}{t_{1R}} \cdot T_R - V_{2L}}, \quad (6)$$

where

$$T_i = a V_{2i} \cdot \frac{1}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} + \frac{\frac{1}{t_{1R}}}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} \cdot V_{2L} \\ + \frac{\frac{1}{t_{1L}}}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} \cdot V_{2R}.$$

The subscript, i , can be replaced by either subscript L or R. Appendix 2 shows the derivation of Equation 6 from Equation 5. The complete derivation of Equation 6 from Equation 4 can be seen by reading Appendix 1 through Appendix 2. Equation 6 differs from Equation 2 (Squires & Fantino, 1971) in three fundamental ways. First, T_L and T_R are scaled in terms of value, as are V_{2L} and V_{2R} . Second, the values of the terminal links are already transformed into inverse functions of their delays; therefore, V_{2R} (as opposed to t_{2L} in the delay-reduction hypothesis) is subtracted in the numerator and V_{2L} in the denominator. Third, the proportion of terminal-link values is multiplied by the ratio of the rates of conditioned reinforcement rather than primary reinforcement. Equation 6 thereby predicts that preference will be more sensitive to the size of the difference between the initial links of the two chain schedules. Another difference between the models is that Equation 6 has different minuends (i.e., T_L and T_R) for the conditioned-reinforcement-value terms. If V_{2L} is greater

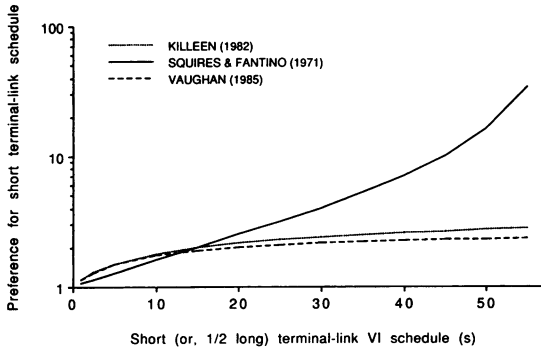


Fig. 2. Predicted preference as a function of the absolute schedule value in the terminal links of a concurrent-chains procedure. Shown are the predictions of Killeen (1982), Squires and Fantino (1971), and Vaughan (1985) for a concurrent-chains procedure with equal initial-link schedules (VI 60 s) and terminal-link VI schedules always in the ratio of 2:1. Preference for the shorter terminal link is plotted on the ordinate.

than V_{2R} , then T_L is greater than T_R , and vice versa. Because this means that the larger terminal-link value (e.g., V_{2L}) is always being subtracted from the smaller minuend (e.g., T_R), the net effect is an enhancement of the discrepancy from 1.0 of the ratio of conditioned reinforcement values than would be obtained given a common value (e.g., T). Basically, the model predicts that the net effective value of a terminal link is the increment in value signaled by the terminal-link stimulus relative to the overall expected value in the conditioning situation. According to Equation 6, melioration predicts matching to the *value accretions* signaled by the terminal links (cf. Rescorla & Wagner, 1972).

Conditioned reinforcement and the context of reinforcement. Each of the models has distinct limitations wherein particular phenomena are outside their respective domains or are simply poorly predicted (see Davison, 1987; Killeen, 1982; Vaughan, 1985; Williams, 1988). For each model, however, the limitations tend to involve complicated situations (e.g., terminal links comprised of chains or multiple schedules) in which behavior is necessarily complexly determined. For situations involving standard concurrent chains with VI terminal links, the models make comparable predictions, and each has been applied to a range of conditions. For instance, each of the models predicts Fantino's (1969a) finding that sensitivity to the terminal-link schedules depends on the absolute size of the initial links relative

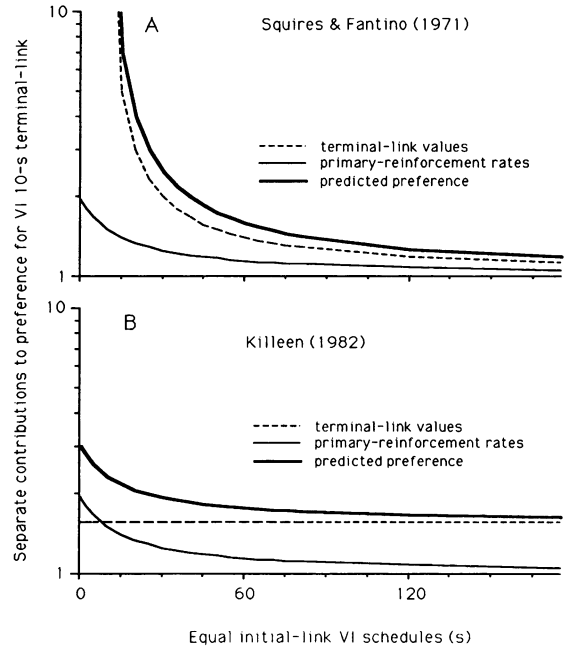


Fig. 3. Predicted ratios of terminal-link values, rates of primary reinforcement, and response rates (preference) as a function of the absolute schedule values in the equal initial links of a concurrent-chains procedure. Panel A shows the predictions of Squires and Fantino (1971) for a concurrent-chains procedure with VI 10-s and VI 20-s terminal links. Panel B shows the predictions of Killeen (1982).

to the absolute size of the terminal links. That is, given fixed and unequal terminal links, the longer the initial-link schedules, the less extreme will be preference for the shorter terminal link; given fixed initial-link delays, the longer the unequal terminal-link delays, the more extreme will be preference for the shorter terminal link. Figure 1 shows the predictions of each model when terminal-link schedules of VI 10 s and VI 20 s are preceded by equal initial links varying in duration from VI 1 s to VI 180 s. The predictions for incentive theory are based on Killeen's (1982, Equation 8) approximation for VI terminal links with q equal to .125. The predictions for melioration theory were derived with a equal to .1. All three models predict that preference, measured as the ratio of responses in the two initial links, for the VI 10-s schedule is highest with short initial-link schedules and increasingly lower as the initial-link schedules are increased. Figure 2 shows the models' predictions when the terminal-link VI schedule requirements are kept in a constant ratio of 2:1 but the absolute

delays increase. All models predict that preference will be a monotonically increasing function of the absolute size of the terminal-link schedules.

Although the predictions of the models are qualitatively similar, overall preference measures tend to obscure the differences in their conceptualizations of the value or strength of conditioned reinforcers in relation to the overall context of reinforcement. This can be seen by graphically separating the contributions of the value and frequency components of the models. For example, Figure 3 shows, for the delay-reduction hypothesis and incentive theory, predictions of the separate contributions to overall preference of (a) the relative terminal-link values and (b) the relative rates of primary reinforcement, each as a function of the equal initial-link schedules leading to VI 10-s and VI 20-s terminal links. The thin solid lines in Panels A and B are identical and show the change in the relative rates of reinforcement. The critical distinction between the models can be seen in the accompanying function (dashed line) in each panel. According to incentive theory (Panel B), the relative values of the terminal links (directive effects of the two terminal links) are unchanged by the initial-link schedules—thus the flat function relating the directive effects to the size of the equal initial links. In contrast, delay reduction (and melioration) treats the values of the conditioned reinforcers as a joint function of their durations and the temporal context in which they occur. If $t_{2L} < t_{2R}$, the ratio $(T - t_{2L}) / (T - t_{2R})$ is a monotonically decreasing function of either of the initial-link schedules with an asymptote of infinity when T approaches t_{2R} from above and an asymptote of 1.0 as T grows very large. Thus the models predict the same net effect but differ as to what determines the eventual result. Preference decreases as the initial links are increased either because (a) the ratios of primary reinforcement rates and conditioned reinforcement values are changing in favor of the VI 20-s terminal link or (b) only the ratio of primary reinforcement rates is changing in favor of the VI 20-s terminal link.

To discriminate the several accounts it is necessary to find conditions in which the effects of changes in the frequencies of primary reinforcement (delay reduction and incentive theory) or conditioned reinforcement (melio-

ration) cannot themselves account for changes in preference for fixed, but unequal, terminal links. Consider the effect of varying one of the initial links in a concurrent-chains schedule with VI 10-s and VI 20-s terminal links while the other initial-link schedule is VI 60 s. If the initial link preceding the VI 10-s (i.e., shorter) terminal link is increased from VI 1 s to VI 60 s, all three models predict decreasing preference for the VI 10-s schedule. Incentive theory does so because the frequency of primary reinforcement on the VI 10-s key is decreasing over conditions. Melioration and delay reduction do so because (a) the relative frequency of primary (or conditioned) reinforcement on the VI 10-s key is decreasing and (b) the relative values of conditioned reinforcement are becoming more similar. If instead, the initial link preceding the VI 20-s (i.e., longer) terminal link is increased, the predictions of the models diverge. Figure 4 shows the predictions of incentive theory, the delay-reduction hypothesis, and melioration when the initial link preceding the VI 20-s (i.e., longer) terminal link is varied. Whereas incentive theory and melioration both predict that preference for the VI 10-s schedule is a monotonically increasing function of the initial link preceding the VI 20-s schedule, the delay-reduction hypothesis predicts that preference is a bitonic function, decreasing as the initial link is increased from 0 s to about 14 s and then increasing as the initial link is lengthened further. Once again, the overall preference functions obscure the similarities and differences among the models. Figure 5 shows the predictions of all three models with separate functions for the relative rates of reinforcement and the relative values of the terminal links. Incentive theory (Figure 5A) predicts monotonically increasing preference for the VI 10-s schedule as the other initial link is increased because of the changing ratio of primary reinforcement rates on the two keys. Delay reduction (Figure 5B) and melioration (Figure 5C), on the other hand, predict that preference will be the result of two opposing influences. Although the relative rate of primary (or conditioned) reinforcement on the VI 10-s key (vs. the VI 20-s key) is increasing, the relative conditioned reinforcement value of the VI 10-s terminal link is decreasing as a function of the initial-link VI schedule preceding the VI 20-s terminal link. The latter is true because

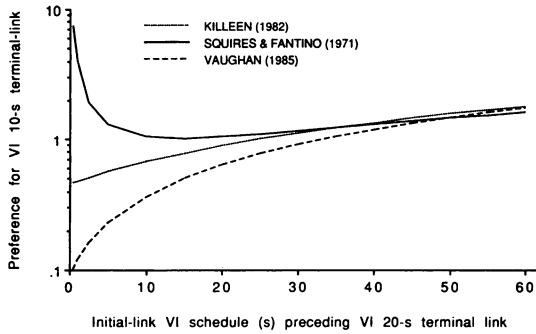


Fig. 4. Predicted preference for the shorter terminal-link schedule (VI 10 s) as a function of the initial-link VI schedule preceding the longer (VI 20 s) of two terminal-link schedules in a concurrent-chains procedure. Shown are the predictions of Killeen (1982), Squires and Fantino (1971), and Vaughan (1985).

the delay reductions signaled by the two terminal links are becoming less discrepant. Thus, although all of the models predict that shortening the schedule leading to the higher valued (i.e., shorter) terminal link will increase preference for that schedule, the predictions of the models diverge when predicting the effect of varying the initial link leading to the lower valued (i.e., longer) terminal link.

EXPERIMENT 1

Experiment 1 investigated preference as a function of the initial-link VI requirement preceding the longer of two terminal links in a concurrent-chains schedule. According to the delay-reduction hypothesis, preference should be a bitonic function of the initial-link schedule, reflecting the joint effects of the rates of primary reinforcement and the conditioned reinforcement values of the two chain schedules. Incentive theory and melioration theory both predict that preference will be a monotonic function of the initial-link schedule, but for fundamentally different reasons. According to Killeen (1982), the conditioned reinforcement values of the terminal-link stimuli are a function only of the terminal-link schedules and therefore are not affected by variations in initial-link schedules. Vaughan's (1985) melioration model, on the other hand, conceptualizes the determinants of conditioned reinforcement value in much the same way as does the delay-reduction hypothesis. The monotonic function predicted by melioration reflects the relatively greater impact of the ra-

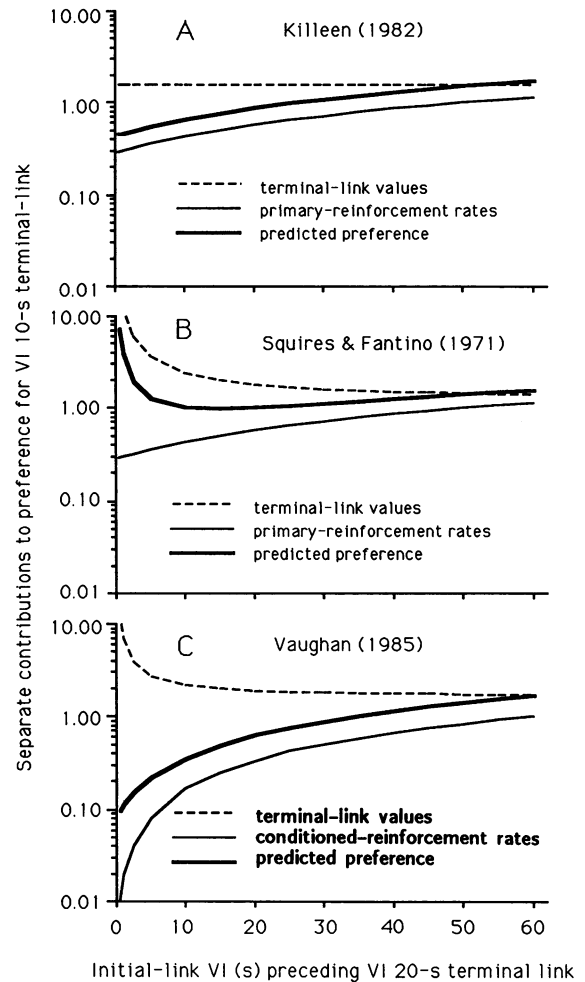


Fig. 5. Predicted ratios of terminal-link values, rates of primary reinforcement, and response rates (preference for the shorter, VI 10-s, terminal link) as a function of the initial link preceding the longer (VI 20 s) of two terminal links in a concurrent-chains procedure. The predictions are those of Killeen (1982), Squires and Fantino (1971), and Vaughan (1985).

tio of conditioned reinforcement rates compared to the ratio of conditioned reinforcement values.

METHOD

Subjects

Four experimentally naive mixed-breed male pigeons were maintained at 80% of their free-feeding weights by additional feeding, if necessary, at the end of each experimental session. The pigeons were housed individually in a colony room, where they were provided with

continuous access to grit and vitamin-enriched water.

Apparatus

Experimental sessions were conducted in four identical standard operant conditioning chambers that were sealed-plywood enclosed boxes with opaque black plastic side walls, sheet aluminum front and back walls, plywood ceilings, and wire mesh floors. In each chamber, the experimental space was 35 cm wide by 36 cm deep by 32 cm high. The front wall contained three translucent 2.5-cm diameter response keys mounted 23 cm above the floor and 7.25 cm apart center to center. A 1-W miniature lamp with a colored plastic cover was located 8.75 cm above each response key. Access to a solenoid-operated grain hopper was available through an opening (5.75 cm by 5 cm) located directly below the center key and 9.5 cm above the floor. When activated, the hopper was illuminated from above by a 1-W miniature lamp. Each key required approximately 0.15 N to operate and could be trans-illuminated from the rear by standard IEE 12-stimulus in-line projectors. Reinforcement consisted of 3-s access to milo during which all keylights and houselights were dark. A 5-cm speaker was mounted above the center of each chamber's ceiling and provided continuous white noise throughout experimental sessions. Data recording and scheduling of experimental events were controlled from an adjacent room by a PDP-8E® computer operating under Systol® software.

Procedure

Preliminary training. All subjects were trained to eat from the grain hopper during the first 1 to 3 days of training. The hopper was raised when the bird was first placed in the chamber and remained raised until the bird ate for 30 s. The hopper was then lowered and raised repeatedly until the bird ate reliably and immediately upon its presentation. Key pecking was engendered using a modified autoshaping procedure in which either the left or right response key was illuminated one of three colors (red, green, or white) for 6 s on the average of every 60 s. At the end of each 6-s trial, the food hopper was raised and illuminated for 3 s and all other chamber lights were dark. A key peck during the 6-s trial immediately produced the hopper, after which the

next trial was begun without the intervening intertrial interval. Autoshaping sessions ended after 40 hopper presentations. During hopper training and autoshaping, the center house-light (bare bulb) was illuminated between hopper presentations.

General procedure. All subjects' responses were reinforced according to a concurrent-chains schedule (Figure 6). In the presence of the two initial-link stimuli, responses were reinforced according to concurrent and independent VI schedules on the left and right keys. On each key, the first response following the lapse of the interval requirement was reinforced by the presentation of the terminal-link stimulus scheduled on that key. Responding in the presence of the terminal-link stimulus was reinforced by food according to a VI schedule. When either terminal link was produced, the other key became dark and timing of the schedules on the dark key was interrupted until the initial links were again present. In all conditions, the VI requirements for the two terminal links were VI 10 s and VI 20 s, and the initial-link schedule leading to the VI 10-s schedule was VI 60 s. The initial link preceding the VI 20-s terminal link was varied across conditions. For all subjects, the initial link preceding the VI 20-s schedule was VI 60 s, VI 14 s, and FI 1 s in successive conditions. Terminal-link key colors and sides were counter-balanced across subjects.

Daily sessions were terminated after 40 reinforcers or 90 min, whichever came first. Each condition remained in effect for a maximum of 45 sessions or until a stability criterion was satisfied. After 15 sessions, the choice proportions for the previous nine sessions were divided into three blocks of three sessions. The stability criterion was satisfied if the means of the three blocks differed by no more than .05 and were not strictly increasing or decreasing.

RESULTS

Figure 7 shows preference for the VI 10-s terminal link averaged over the last five sessions of each condition for individual subjects. Data are plotted as choice ratios for the VI 10-s schedule—that is, initial-link responses on the VI 10-s key divided by the initial-link responses on the VI 20-s key. For each of 4 pigeons, response ratios were a bitonic function of the initial link leading to the VI 20-s (i.e., longer) terminal link. Preference de-

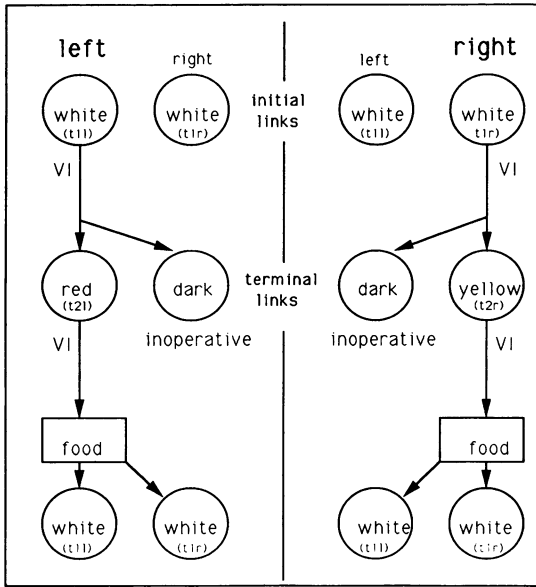


Fig. 6. The concurrent-chains procedure. See text for details.

creased as the initial-link schedule leading to the VI 20-s terminal link decreased from VI 60 s to VI 14 s and then increased as the initial-link schedule was further decreased to FI 1 s. Averaged across subjects, preference for the VI 10-s schedule was 3.42, 1.18, and 1.73, respectively, when the initial-link schedule was FI 1 s, VI 14 s, and VI 60 s. The choice ratios, left and right initial-link responses, total initial-link time, total terminal-link time, left and right terminal-link entries, and number of sessions in each condition for each subject are shown in Table 1.

DISCUSSION

Preference for the shorter of two terminal links in a concurrent-chains procedure was a bitonic function of the initial link preceding the longer of two terminal links. Short and long initial-link VI requirements produced higher preference for the VI 10-s terminal link than did an intermediate initial-link VI requirement. This finding is consistent with the delay-reduction hypothesis, which predicts two opposing effects of variations in the initial-link requirement. As the initial link leading to the longer of two terminal links is decreased, the ratio of conditioned reinforcement values becomes larger in favor of the VI 10-s terminal link and the ratio of reinforcement rates changes

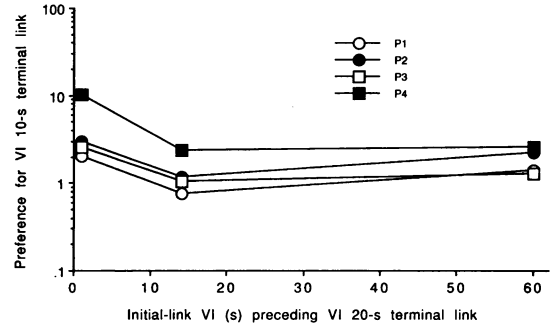


Fig. 7. Preference for the shorter (VI 10 s) of two terminal links as a function of the initial-link VI schedule preceding the longer (VI 20 s) of two terminal links for Subjects P1 through P4.

in favor of the VI 20-s terminal link. The simultaneous effects of these changes are, respectively, to decrease preference and increase preference for the lower valued terminal link. If the values of the terminal-link stimuli were a constant function of their delays, as suggested by incentive theory, then preference should have been a monotonic function of the initial-link schedule, reflecting, in effect, matching to the frequencies of different amounts of reinforcement on the two keys (Catania, 1963; de Villiers & Millenson, 1972; Dunn, 1982; Fantino, Squires, Delbrück, & Peterson, 1972). Instead, the results suggest that the values of the terminal-link stimuli were themselves changing as a function of the initial link preceding the VI 20-s terminal link.

Although these results are consistent with the predictions of the delay-reduction hypothesis, the FI 1-s initial-link condition imposed a severe limit on the potential number of initial-link responses on the VI 20-s key. Because the initial links were presented immediately after reinforcement, even a slight latency to get from the hopper to the key would result in very few responses per terminal-link entry on the FI 1-s key. Almost any responding on the VI 60-s initial link might have substantially shifted the ratio of responses away from the short initial-link key. Thus, the findings reported here might reflect a simple measurement artifact. A review of the literature on concurrent-chains studies suggests otherwise. Although they did not apply their results to the present issues, Fantino and Davison (1983) reported the results of over 50 concurrent-chains conditions, some of which replicate the

Table 1

Experiment 1 results. All data are averages of the last five sessions per condition, and all times are in seconds.

Subject	Initial-link VI	Preference for VI 10 s	Left initial responses	Right initial responses	Total initial time	Total terminal time	Left entries	Right entries	Sessions
P1	VI 60 s	1.43	486	339	1,306	654	18	22	40
	VI 14 s	0.75	166	220	493	661	7	33	35
	FI 1 s	1.97	73	37	218	786	3	37	32
P2	VI 60 s	2.19	296	647	1,262	625	21	19	35
	VI 14 s	1.27	220	279	597	732	31	9	40
	FI 1 s	3.21	35	112	498	680	35	5	32
P3	VI 60 s	1.26	320	255	1,283	663	20	20	40
	VI 14 s	1.05	128	121	617	734	9	31	31
	FI 1 s	2.34	80	34	431	708	6	34	21
P4	VI 60 s	2.3	407	937	1,603	557	19	21	40
	VI 14 s	1.96	232	455	569	749	31	9	38
	FI 1 s	9.28	34	319	399	706	34	6	33

findings of Experiment 1 using different terminal-link schedules. In other conditions, they varied the initial link leading to the shorter of two terminal links. Figure 8 shows the results of Fantino and Davison when the initial-link schedule preceding either the longer (VI 40 s) or shorter (VI 20 s) of two terminal links was varied. Preference in each case is plotted for the terminal link whose initial link is being varied. As the initial link preceding the VI 20-s (i.e., shorter) terminal link increased from VI 15 s to VI 180 s, preference for the VI 20-s terminal link decreased monotonically—that is, the less frequent the terminal link, the less it was preferred. However, as the initial link preceding the VI 40-s (i.e., longer) terminal link was increased from VI 0 s to VI 180 s, preference for the VI 40-s schedule increased—that is, the less frequent the terminal link, the more it was preferred. The lower function, which replicates the findings of Experiment 1, is increasing over the same range of initial-link schedules in which the upper function is decreasing. If the lower function were the result of a measurement artifact, one would expect the same effect in the upper function because of the same limitations on the number of short initial-link responses. Instead, the results are consistent with the delay-reduction hypothesis, which predicts that the relative conditioned reinforcement values are changing in favor of the shorter terminal link as either initial link becomes shorter.

Fantino and Davison's (1983) data suggest

another reason to reject the argument that there is a measurement artifact responsible for the results of Experiment 1. According to that argument, the function relating preference to variations in the initial link should have a minimum at a relatively short initial-link requirement. Only when the varied initial link is so short as to seriously limit the potential number of responses should the ratio of responses shift in favor of the longer initial link. But in Fantino and Davison's experiment, preference for the VI 20-s terminal link decreases as the other initial link increases over a much wider range than is consistent with this view (e.g., between VI 30 s and VI 60 s). Again, this is consistent with the delay-reduction hypothesis, which predicts that the initial-link value at which the preference function shifts from a negative to a positive slope does not depend on the absolute size of the initial link. Instead, the minimum of the function is itself a function of the terminal-link durations. The minimum for a given set of terminal links can be found by differentiating delay reduction with respect to t_{1R} and then finding where the derivative is equal to zero. Doing so shows that the partial derivative, $f'(t_{1R})$, equals 0 when

$$t_{1R} = \sqrt{t_{2R}^2 - t_{2R} \cdot t_{2L}}.$$

Figure 9 shows the predictions of the delay-reduction hypothesis for the longer of two terminal links as a function of the duration of its initial link for three different sets of terminal-

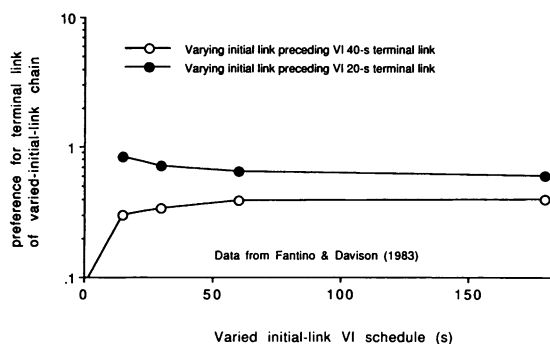


Fig. 8. Preference for VI 20 s (filled points) and preference for VI 40 s (open points) as a function, respectively, of the initial links preceding the VI 20-s and the VI 40-s terminal links in the concurrent-chains procedure of Fantino and Davison (1983).

link values: VI 10 s and VI 20 s, VI 10 s and VI 30 s, and VI 30 s and VI 50 s. For these terminal-link pairs, the minimum shifts to longer initial-link schedules with longer terminal links.

EXPERIMENT 2

Experiment 2 investigated preference as a function of the initial link leading to the longer of two terminal links for different groups of subjects having different terminal-link schedules. According to the delay-reduction hypothesis, the minima of the functions for the different groups should depend upon the terminal-link schedules rather than upon the absolute initial-link schedule. For the first group (Group 10/20), responses were reinforced successively according to concurrent chains with VI 10-s and VI 20-s terminal links, FI 10-s and FI 20-s terminal links, and VI 10-s and VI 20-s terminal links. For the second group (Group 30/50), responses were reinforced according to concurrent chains with VI 30-s and VI 50-s terminal links. For the third group (Group 10/30), responses were reinforced according to concurrent chains with VI 10-s and VI 30-s terminal links.

METHOD

Subjects

Twelve experimentally naive mixed-breed male pigeons served as in Experiment 1.

Apparatus

Experimental sessions were conducted in 12 operant conditioning chambers, four of which

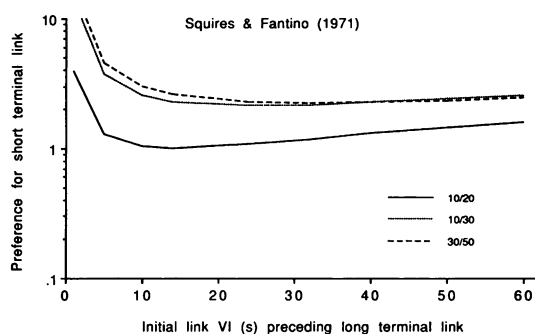


Fig. 9. Squires and Fantino's (1971) predictions of preference for the shorter (VI 10 s, VI 10 s, and VI 30 s in successive functions, top to bottom) of two terminal links as a function of the initial-link VI schedule preceding the longer (VI 20 s, VI 30 s, and VI 50 s in successive functions, top to bottom) terminal link in a concurrent-chains procedure.

were those used in Experiment 1 and two more of identical design. The other six chambers were opaque black PVC cylinders, 36 cm high and 33 cm in diameter, each with a wire mesh floor and opaque black ceiling. Three translucent 2.5-cm response keys were mounted 24 cm above the floor and 7.25 cm apart, measured along the circumference, center to center. A 1-W miniature lamp with a colored plastic cover was located 8.75 cm above each response key. The grain hopper was an opening (5.75 cm by 5 cm) located directly below the center key and 9.5 cm above the floor. For all chambers, each key required approximately 0.15 N to operate and could be transilluminated from the rear by standard IEE 12-stimulus in-line projectors. Reinforcement consisted of 3-s access to milo during which all keylights and houselights were dark. A 5-cm speaker was mounted above the center of each chamber's ceiling and provided continuous white noise throughout experimental sessions. Data recording and scheduling of experimental events were controlled from an adjacent room by a PDP-8E® computer operating under Systol® software.

Procedure

After preliminary training (see Experiment 1), responses were reinforced according to a concurrent-chains schedule (Figure 6). The procedure differed from Experiment 1 in that a 1-s changeover delay was imposed between responses on each initial link and the presentation of a terminal link on the other key: The

first response on a key following a response on the other key started a 1-s delay during which responses did not produce a terminal link.

Group 10/20. Four subjects' (S1–S4) responses were reinforced according to concurrent-chains schedules with VI 10-s versus VI 20-s, FI 10-s versus FI 20-s, and VI 10-s versus VI 20-s terminal-link schedules in successive series of conditions. The initial-link schedule preceding the VI (or FI) 10-s terminal link was always VI 60 s. In each series the initial link preceding the VI (or FI) 20-s terminal link was varied over conditions. In the first series (VI 10 s vs. VI 20 s) the initial-link schedule was VI 60 s, VI 14 s, and VI 2 s in successive conditions. In the second series (FI 10 s vs. FI 20 s) the initial-link schedule was VI 2 s, VI 14 s, and VI 60 s in successive conditions. In the third series (again, VI 10 s vs. VI 20 s) the initial-link schedule was VI 14 s, VI 32 s, and VI 4 s in successive conditions.

Group 30/50. Four subjects' (S5–S8) responses were reinforced according to concurrent-chains schedules with VI 30-s versus VI 50-s terminal-link schedules. The initial-link schedule preceding the VI 30-s terminal link was always VI 60 s. The initial link preceding the VI 50-s terminal link was varied over conditions: the initial-link schedule was VI 60 s, VI 32 s, VI 14 s, and VI 4 s in successive conditions. The latter three conditions were then replicated: The initial-link schedule was VI 32 s, VI 14 s, and VI 4 s in successive conditions.

Group 10/30. Four subjects' (S9–S12) responses were reinforced according to a concurrent-chains schedule with VI 10-s versus VI 30-s terminal-link schedules. The initial-link schedule preceding the VI 10-s terminal link was always VI 60 s. The initial link preceding the VI 30-s terminal link was VI 5 s, VI 60 s, VI 10 s, and VI 24 s in successive conditions. For Subject S9 only, after the VI 60-s condition, the side positions of the chain schedules were reversed and the VI 5-s and VI 60-s initial-link conditions were repeated. Data are not reported from the first two conditions for Subject S9. This change was implemented because, in the last five sessions of the original VI 60-s condition, Subject S9 emitted no responses on the longer terminal-link key and would not have been sensitive to subsequent initial-link variations.

Daily sessions were terminated after 40 re-

inforcers or 90 min, whichever event occurred first. Each condition remained in effect for a maximum of 35 sessions or until choice ratios were stable (see Experiment 1).

RESULTS

The obtained choice ratios, left and right initial-link responses, total initial-link time, total terminal-link time, left and right terminal-link entries, and number of sessions in each condition for each subject are shown in Table 2. Figure 10 (Panels A, B, and C) shows preference for the shorter terminal link averaged over the last nine sessions of each condition for individual subjects in Group 10/20. Data are plotted as choice ratios for the shorter terminal-link schedule—that is, initial-link responses on the short-terminal-link key divided by the initial-link responses on the long-terminal-link key. In general, preference for the VI (or FI) 10-s terminal link was either a bitonic or inverse function of the initial link preceding the VI (or FI) 20-s terminal link, the only exception being the function for Subject S1 in the original VI initial-link conditions (Panel A). The group mean preferences for each series of conditions are shown in Figure 10, Panel D. The group mean preferences for the first series with VI initial links were 1.03, 1.02, and 1.59, respectively, when the varied initial link was VI 2 s, VI 14 s, and VI 60 s. The group mean preferences for the FI terminal-link series were 5.39, 2.17, and 5.93, respectively, when the varied initial link was VI 2 s, VI 14 s, and VI 60 s. The group mean preferences for the second series with VI initial links were 1.40, 1.09, and 1.16, respectively, when the varied initial link was VI 4 s, VI 14 s, and VI 32 s. Because of the intervening FI terminal-link conditions, the data from the two VI terminal-link conditions were not combined to produce a single function. Analyses of variance for the main effect of initial link were significant for the second set of VI conditions, $F(3, 2) = 5.7$, $p = .04$, and for the FI terminal-link conditions, $F(3, 2) = 10.79$, $p = .01$, but not for the original VI series, $F(3, 2) = 2.47$, $p = .17$. Planned comparisons for linear and quadratic trends resulted in a significant ANOVA for quadratic trend for the FI series, $F(1, 3) = 20.70$, $p = .02$, and for linear trend for the second VI series, $F(1, 3) = 12.97$, $p = .04$.

Figure 11 shows preference for the shorter terminal link averaged over the last nine ses-

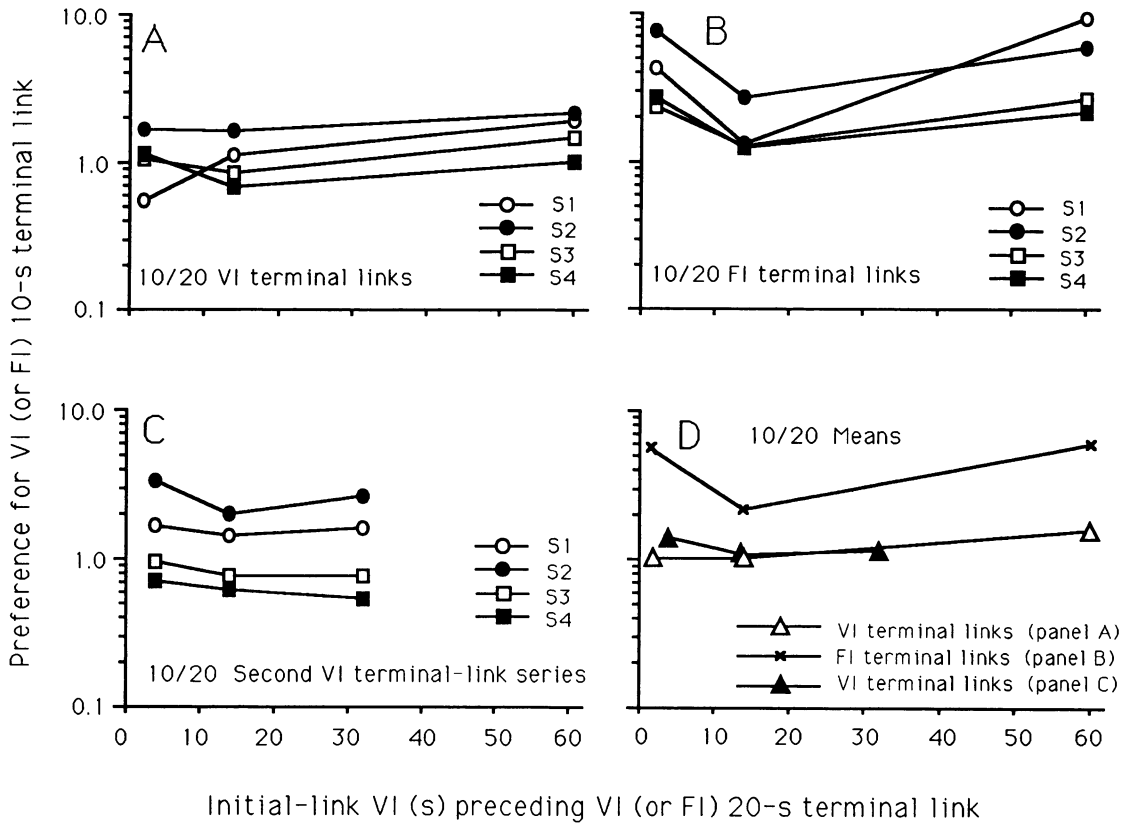


Fig. 10. Preference for the shorter of two terminal links as a function of the initial-link VI schedule preceding the longer terminal link for Subjects S1 through S4 (Group 10/20). Panel A shows preferences in the first series of VI terminal links. Panel B shows preferences from the series with FI terminal links. Panel C shows preferences from the second series of VI terminal links. Panel D shows group mean preferences for each condition.

sions for each subject and condition for Group 30/50. Data are averaged over replications of initial-link values. For 2 of 4 subjects (S6 and S7), preference was a monotonically decreasing function of the initial link preceding the VI 50-s terminal link. For Subject S5 and S8, preference had a local minimum at VI 14 s. Also shown in Figure 11 are the group mean preferences averaged over subjects. The group mean preferences were 3.46, 2.56, 2.14, and 1.93, respectively, when the varied initial link was VI 2 s, VI 14 s, VI 32 s, and VI 60 s. An analysis of variance detected no significant effect of initial-link schedule, $F(3, 3) = 3.41$, $p = .07$, reflecting the fact that between VI 4 s and VI 60 s the functions were nonmonotonic for 2 subjects and strictly decreasing for 2 subjects.

Figure 12 shows preference for the shorter terminal link averaged over the last nine sessions for each subject and condition for Group

10/30. Again, individual subjects produced preferences that were either a bitonic function (Subjects S10 and S12) or inverse function (Subjects S9 and S11) of the initial link preceding the longer of two terminal links. The group mean preferences (also shown in Figure 12) were 3.81, 3.29, 2.48, and 2.15, respectively, when the varied initial link was VI 5 s, VI 10 s, VI 24 s, and VI 60 s. An analysis of variance detected no significant effect of initial-link schedule, $F(3, 3) = 1.8$, $p = .21$, reflecting the fact that between VI 10 s and VI 60 s the functions were decreasing for 2 subjects and bitonic for 2 subjects.

DISCUSSION

The results of Experiment 2 replicate those of Experiment 1 in that preference for the shorter of two terminal links was not an increasing function of the initial-link VI requirement preceding the longer of the two ter-

Table 2

Experiment 2 results. All data are averages of the last nine sessions per condition, and all times are in seconds.

Subject	Initial-link VI	Preference for VI 10 s	Left initial responses	Right initial responses	Total initial time	Total terminal time	Right entries	Left entries	Sessions
S1	VI 60 s	1.93	1,247	647	1,302	515	22	18	27
	VI 14 s	1.13	505	448	770	733	9	31	21
	VI 2 s	0.55	90	164	307	716	4	36	27
	VI 2 s (FI)	4.33	529	122	886	677	12	28	23
	VI 14 s (FI)	1.32	300	227	791	814	11	29	35
	VI 60 s (FI)	9.24	1,437	155	1,683	556	26	14	19
	VI 14 s	1.42	499	353	669	667	11	29	27
	VI 32 s	1.6	824	514	1,157	660	16	24	35
S2	VI 4 s	1.66	276	166	549	929	7	33	16
	VI 60 s	2.16	742	1,604	1,364	581	19	21	37
	VI 14 s	1.63	413	675	677	817	30	10	22
	VI 2 s	1.66	137	227	318	713	35	5	27
	VI 2 s (FI)	30.16	59	1,790	1,771	647	13	24	25
	VI 14 s (FI)	10.73	133	1,430	1,701	632	18	13	35
	VI 60 s (FI)	23.43	95	2,220	1,941	514	10	30	18
	VI 14 s	2.02	306	619	757	709	29	11	29
S3	VI 32 s	2.66	395	1,049	1,277	703	23	17	30
	VI 4 s	3.37	150	505	959	1,085	31	9	20
	VI 60 s	1.5	1,054	703	1,675	652	19	21	26
	VI 14 s	0.85	374	438	585	721	9	31	27
	VI 2 s	1.07	154	144	361	819	4	36	35
	VI 2 s (FI)	2.37	189	80	721	733	10	30	19
	VI 14 s (FI)	1.26	263	209	888	789	11	29	35
	VI 60 s (FI)	2.63	811	308	1,554	555	22	18	33
S4	VI 14 s	0.78	278	354	623	633	9	31	34
	VI 32 s	0.78	521	666	1,166	621	14	26	18
	VI 4 s	0.96	168	174	484	859	6	34	18
	VI 60 s	1.02	1,295	1,322	1,366	592	21	19	26
	VI 14 s	0.68	611	417	532	691	31	9	26
	VI 2 s	1.14	206	236	284	779	37	3	21
	VI 2 s (FI)	2.71	156	424	456	743	34	6	24
	VI 14 s (FI)	1.24	583	722	720	735	30	10	18
S5	VI 60 s (FI)	2.17	703	1,528	1,370	557	16	24	32
	VI 14 s	0.62	617	384	531	664	31	9	22
	VI 32 s	0.54	1,099	588	973	644	25	15	26
	VI 4 s	0.71	281	199	282	916	37	3	20
		Average preference for VI 30 s							
	Initial-link VI								
	VI 60 s	1.76	471	268	1,500	1,543	20	19	37
	VI 32 s	2.18	681	199	1,281	1,538	18	22	25
S6	VI 14 s	2.01	340	198	746	1,982	10	30	33
	VI 4 s	2.51	211	163	532	1,620	9	31	32
	VI 32 s		653	414	1,004	1,612	15	25	22
	VI 14 s		585	262	755	1,783	12	28	30
	VI 4 s		229	12	3,316	1,042	28	1	18
	VI 60 s	1.95	537	1,045	1,280	1,580	20	20	40
	VI 32 s	2.13	570	1,090	986	1,732	24	16	35
	VI 14 s	3.34	225	718	725	1,559	27	13	21
S7	VI 4 s	5.47	145	699	698	1,851	31	9	17
	VI 32 s		372	917	930	1,489	22	18	24
	VI 14 s		214	751	773	1,737	27	13	33
	VI 4 s		139	853	892	1,678	25	15	22
	VI 60 s	2.09	667	1,392	1,367	1,489	17	23	27
	VI 32 s	2.38	462	836	1,097	1,759	24	16	21

Table 2 (Continued)

Subject	Initial-link VI	Average preference for VI 30 s	Left initial responses	Right initial responses	Total initial time	Total terminal time	Right entries	Left entries	Sessions
S8	VI 14 s	3.93	303	652	743	1,699	27	13	33
	VI 4 s	6.13	157	752	766	1,773	29	11	33
	VI 32 s		405	1,228	1,121	1,492	22	18	22
	VI 14 s		176	1,231	1,070	1,684	24	16	20
	VI 4 s		105	854	822	1,849	25	15	20
	VI 60 s	1.92	950	494	1,560	1,541	23	17	28
	VI 32 s	1.89	1,014	486	1,018	1,786	17	23	26
	VI 14 s	1.62	497	385	734	1,914	11	29	35
	VI 4 s	1.71	326	185	519	1,916	7	33	35
	VI 32 s		680	410	878	1,696	16	24	35
	VI 14 s		527	246	713	1,674	13	27	29
	VI 4 s		256	156	487	1,722	8	32	17
	Initial-link VI	Prefer- ence for VI 10 s							
S9	VI 5 s	6.10	124	759	1,078	825	24	16	24
	VI 60 s	1.06	687	729	1,403	779	19	21	35
	VI 10 s	6.10	153	931	986	944	21	19	16
	VI 24 s	3.80	219	832	1,164	803	23	17	25
S10	VI 5 s	4.78	518	108	1,288	922	17	23	20
	VI 60 s	3.72	1,125	303	1,185	718	23	17	25
	VI 10 s	2.83	517	183	885	1,138	10	30	35
	VI 24 s	2.35	791	336	970	901	14	26	27
S11	VI 5 s	4.35	685	157	870	990	11	29	23
	VI 60 s	2.88	1,388	482	1,219	897	20	20	49
	VI 10 s	4.30	766	178	752	906	14	26	22
	VI 24 s	3.60	1,069	297	1,147	864	17	23	28
S12	VI 5 s	1.67	281	169	436	1,055	8	32	22
	VI 60 s	1.88	1,039	553	1,260	741	21	19	20
	VI 10 s	1.57	412	262	632	977	10	30	33
	VI 24 s	1.18	644	547	831	985	13	27	35

minal links, as required by incentive theory and melioration. Consistent with the predictions of the delay-reduction hypothesis, preference for the long terminal link was either an inverse function of its frequency or a bitonic function of its frequency; this result supports the hypothesis that the values of the terminal links were changing as a function of the overall expected delay to reinforcement. The fact that many subjects produced strictly decreasing functions argues against the view that the results of Experiment 1 reflected a measurement artifact. VI 24-s and VI 32-s initial links do not substantially restrict the opportunity to respond relative to VI 60-s initial links, yet some subjects (e.g., S9 and S6) still produced higher preferences when the initial-link schedules were VI 24 s and VI 32 s than when they were VI 60 s. Thus, these results replicate those of Fantino and Davison (1983) in which

the inverse functions did not depend on initial-link schedules so short as to restrict the opportunity to respond.

The second, more tentative, finding of Experiment 2 was that the point of inflection appeared to shift as a function of the terminal links, again supporting the predictions of the delay-reduction hypothesis. For Group 10/20, the VI 14-s initial link produced lower mean preferences than all other initial-link schedules. However, not all subjects produced an explicit minimum in each of the series of initial links. For Group 10/30, the mean function was monotonically decreasing, but the 2 subjects with explicit minima produced their lowest preferences when responding under the VI 24-s initial link. For Group 30/50, the 2 subjects with explicit minima produced their lowest preferences with the VI 14-s initial link. For both these groups, however, 2 other sub-

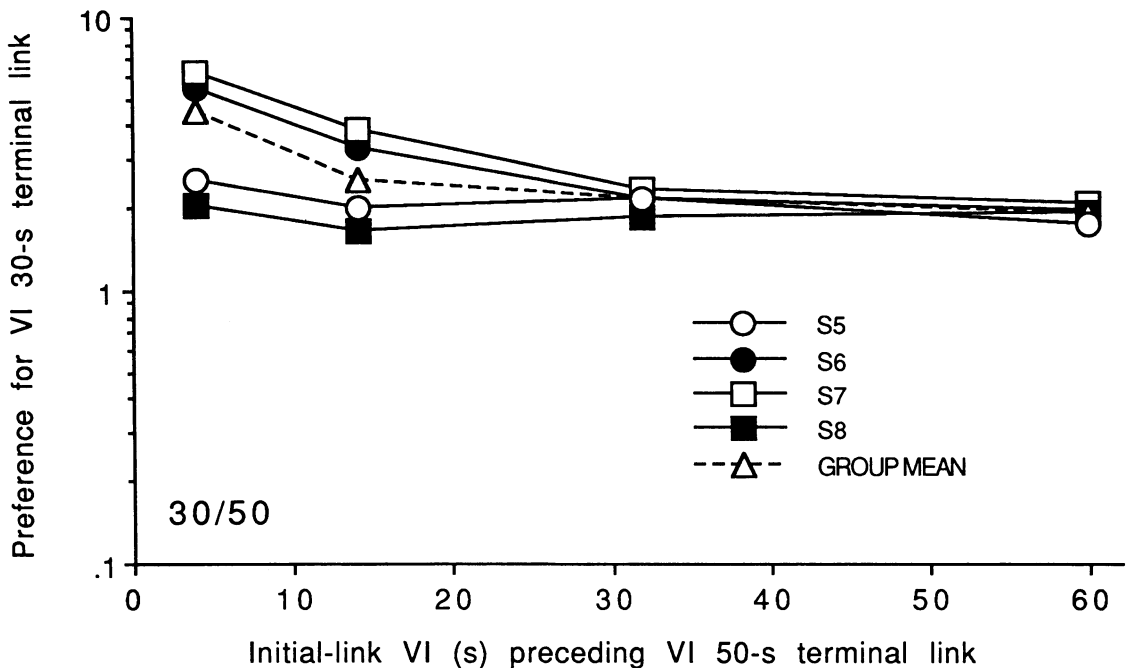


Fig. 11. Preference for the shorter (VI 30 s) of two terminal links as a function of the initial-link VI schedule preceding the longer (VI 50 s) terminal link for Subjects S5 through S8 (Group 30/50). Data are averaged over replications with the same initial-link schedules. The group mean preferences are also plotted.

jects produced monotonically decreasing functions. A more complete assessment of the location of the minima of the functions would require a larger set of initial-link schedules than those studied here. Without a larger range of conditions it is not known whether the actual minima lie between the points in the present study or even at initial-link values exceeding VI 60 s (the longest requirement of the present study). Also, the particular terminal-link schedules studied here were not optimal, because the predictions and results for Groups 10/30 and 30/50 were very similar. Their combined results appear to be different than those of Group 10/20, but the difference between them did not contribute much to clarifying the effects of the present manipulations.

GENERAL DISCUSSION

The most direct implication of these results is that the reinforcing values of the terminal links of a concurrent-chains schedule are not determined solely by the schedules (i.e., delays) imposed in the terminal links. Where bitonic functions were not obtained, preference changed in the direction opposite that pre-

dicted by the assumption of fixed terminal-link values. That is, if it is assumed that the terminal links had constant values, then these results are tantamount to countermatching—the higher the frequency of the fixed-value reinforcer, the lower was preference for that reinforcer. Instead, the values of the terminal links appear to be determined jointly by their associated schedules and the overall context (rate of reinforcement) in which they occur. Although Fantino (1969a, 1969b) first suggested this relationship 22 years ago, no clear and compelling evidence has forced its acceptance. To the extent that the present results constitute such evidence, most contemporary models of conditioned reinforcement and concurrent-chains performance will need a careful reassessment. It may be, as argued by Davison (1987), that the different models—developed in response to different situations—have each uncovered important relations not incorporated by delay reduction. For example, other models have made better quantitative predictions than delay reduction when concurrent chains contain FI terminal links (e.g., Davison & Temple, 1973) or terminal links themselves comprised of chain schedules (e.g., Killeen,

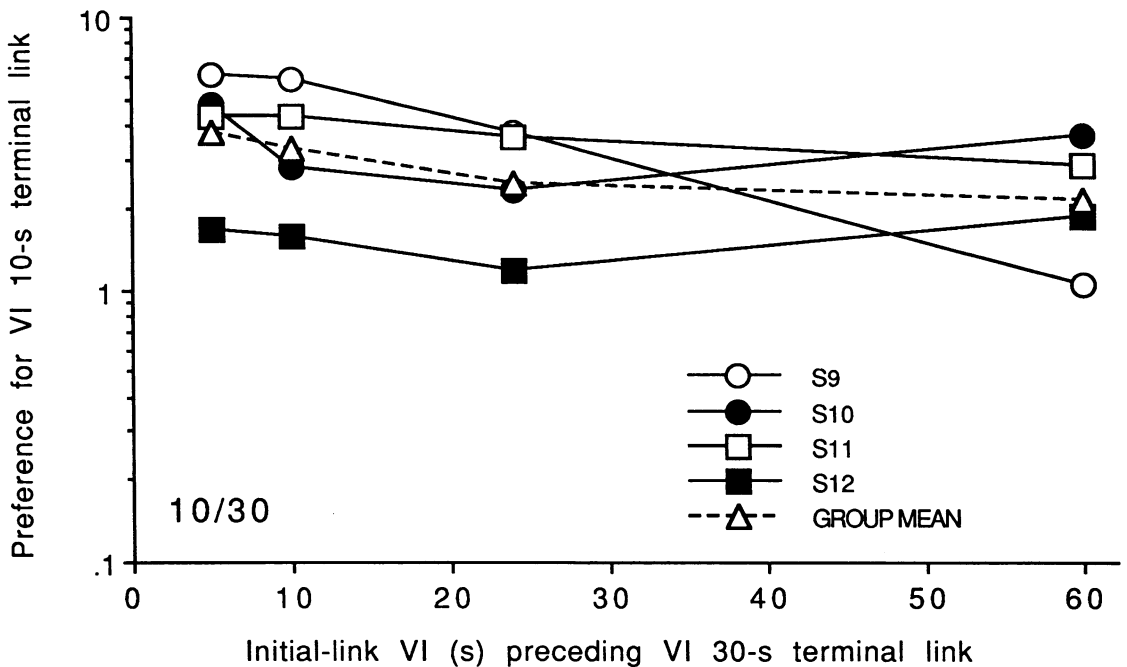


Fig. 12. Preference for the shorter (VI 10 s) of two terminal links as a function of the initial-link VI schedule preceding the longer (VI 30 s) terminal link for Subjects S9 through S12 (Group 10/30). The group mean preferences are also plotted.

1982). However, it remains to be seen what features of the models can be separated from their basic assumption that terminal-link values are a function solely of terminal-link schedules.

Much of the strength of all concurrent-chains models has resided in their shared assumption that the relative rate of reinforcement (either primary or conditioned) plays a major role in determining preference. The different way in which each model has formulated this role has contributed much to the differences among their predictions. For instance, delay reduction and melioration predicted different results for the present studies, but not primarily because of differences between their conceptions of conditioned-reinforcement value. Recall from Figure 5 that the delay-reduction hypothesis and melioration are essentially identical in terms of the two predicted effects of varying the initial link preceding the longer of two terminal links. The overall predictions of the models were qualitatively different, however, mainly because Vaughan (1985) predicted preference as a function of the ratio of conditioned-reinforcement rates, whereas Squires and Fantino (1971) used the rates of primary

reinforcement. Because the ratio of conditioned reinforcement rates changes more quickly with variations in initial-link schedules than does the ratio of primary reinforcement rates, the effect of the terminal-link values exerts less of an effect in Vaughan's model. However, if it is assumed that sensitivity to the rates of conditioned reinforcement need not be perfect, the melioration model (i.e., Equation 6) can be modified by raising the ratio of conditioned-reinforcement rates to a power less than 1.0 and thereby increasing the relative influence of the ratio of terminal-link values. This simple modification allows melioration theory to predict the effects reported here without changing the assumptions of the model. If, for example, the ratio of conditioned reinforcement rates is raised to the power of $\frac{1}{2}$ (cf. Fantino & Davison, 1983), melioration (like delay reduction) predicts a bitonic function for Experiment 1. As such, the present results are not fundamentally challenging to Vaughan's (1985) model. Whether the ratio of terminal-link values should be multiplied by the ratio of conditioned reinforcement rates or the ratio of primary reinforcement rates is not presently known and does not bear directly on how con-

ditioned reinforcement value is determined. As models of conditioned reinforcement value, neither the delay-reduction hypothesis nor melioration theory would be challenged by either outcome.

As discussed by Williams (1988), there is another reason to accept the general conditioning view proposed by the delay-reduction hypothesis. Because classical conditioning generally is assumed to be the process underlying the development of conditioned reinforcers (cf. Ellison & Konorski, 1964; Mackintosh, 1974, pp. 233–250; Skinner, 1938, p. 245), Williams argued that any model of conditioned reinforcement must necessarily incorporate the basic relations found to be important in classical conditioning. In particular, the “ratio effect” (Gibbon, Baldock, Locurto, Gold, & Terrace, 1977; Gibbon & Balsam, 1981; Terrace, Gibbon, Farrell, & Baldock, 1975), studied primarily in autoshaping procedures with pigeons (Brown & Jenkins, 1968), is precisely that predicted by the delay-reduction hypothesis. In a typical autoshaping procedure, food occasionally is presented response independently to a food-deprived pigeon in a standard operant conditioning chamber. A keylight is illuminated several seconds before each food presentation so that the sequence of events is identical to the standard classical conditioning procedure. The keylight is the formal conditioned stimulus (CS), and the food is the formal unconditioned stimulus (US). Gibbon et al. (1977) found that the acquisition of auto-shaped key pecking was a function of the relative, rather than the absolute, durations of the CS and the interfood interval. In general, key pecking was not acquired when the ratios of the average interfood interval (i.e., T) to the CS duration (t) were less than or equal to approximately 1.0. T/t ratios nearer to .5 produced acquisition in less than 10 trials (CS-US pairings). Thus, the value (eliciting efficacy) of a Pavlovian CS was a function of the ratio of the interfood interval to the CS duration. Consistent with the arguments presented here, Gibbon et al. argued that earlier accounts formulated in terms of absolute trial (i.e., CS) durations (Ricci, 1973) or absolute intertrial intervals (Terrace et al., 1975) fundamentally misrepresent the conditioning situation. The effect of pairing a given-duration CS with food depends on the CS duration in relation to the average interfood interval. The

relationship between the delay-reduction hypothesis and the important relations of the ratio effect can be shown by considering the implications of the ratio effect for stimulus strength. Recall that the number of trials to acquisition was an inverse function of the T/t ratio in autoshaping, and that ratios around 1.0 or lower produced no acquisition. Accordingly, the strength of conditioning must be a direct function of T/t , and the function must approach 0 as T/t approaches 1.0. The simplest way to accomplish this is to subtract 1.0 from the ratio so that T/t approaches 0 as t approaches T . Thus the strength (S) of a food-paired stimulus is

$$S = \frac{T}{t_{2L}} - 1.$$

Substituting for 1,

$$S = \frac{T}{t_{2L}} - \frac{t_{2L}}{t_{2L}} = \frac{T - t_{2L}}{t_{2L}},$$

and the relative strengths of two different stimuli, S_L and S_R , can be written

$$\frac{S_L}{S_R} = \frac{T - t_{2L}}{T - t_{2R}} \cdot \frac{t_{2R}}{t_{2L}},$$

which is the same as delay reduction with the addition of a role for the immediacies of primary reinforcement in the terminal links. If the values of the terminal-link stimuli are measured properly as the ratio of T/t , then, for a given pair of terminal links, the ratio model predicts a constant proportional bias relative to delay reduction. Thus, the delay-reduction effect is not limited to the development of instrumental conditioned reinforcement strength or to situations involving concurrent chains. Instead, stimulus conditioning seems to be generally dependent on the overall context of reinforcement.

The relations formalized in the delay-reduction hypothesis have recently been the point upon which concurrent-chains models seem to be converging. Killeen and Fantino (1990) showed that a modification in the assumptions of incentive theory would make its molar predictions indiscriminable from those of delay reduction. Luco (1990) showed how the delay-reduction effect could be predicted from the assumptions of melioration theory. The present paper showed the formal similarity between Vaughan's (1985) melioration model and

the delay-reduction model of Squires and Fantino (1971). The delay-reduction effect also is predicted by contemporary models of classical conditioning (Gibbon & Balsam, 1981; see also Rescorla & Wagner, 1972). At present, each of the models assumes a different set of underlying mechanisms, but there is a growing consensus that the value of a conditioned stimulus depends on the context of reinforcement in which stimulus-reinforcer pairings occur.

REFERENCES

- Brown, P. L., & Jenkins, H. M. (1968). Auto-shaping of the pigeon's key-peck. *Journal of the Experimental Analysis of Behavior*, **11**, 1-8.
- Catania, A. C. (1963). Concurrent performances: A baseline for the study of reinforcement magnitude. *Journal of the Experimental Analysis of Behavior*, **6**, 299-300.
- Davison, M. C. (1987). The analysis of concurrent-chain performance. In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 5. The effect of delay and intervening events on reinforcement value* (pp. 225-241). Hillsdale, NJ: Erlbaum.
- Davison, M. C., & Temple, W. (1973). Preference for fixed-interval schedules: An alternative model. *Journal of the Experimental Analysis of Behavior*, **20**, 393-403.
- de Villiers, P. A., & Millenson, J. R. (1972). Concurrent performances: A baseline for the study of conditioned anxiety. *Journal of the Experimental Analysis of Behavior*, **18**, 287-294.
- Dunn, R. M. (1982). Choice, relative reinforcer duration, and the changeover ratio. *Journal of the Experimental Analysis of Behavior*, **38**, 313-319.
- Ellison, G. D., & Konorski, J. (1964). Separation of the salivary and motor response in instrumental conditioning. *Science*, **146**, 1071-1072.
- Fantino, E. (1969a). Choice and rate of reinforcement. *Journal of the Experimental Analysis of Behavior*, **12**, 723-730.
- Fantino, E. (1969b). Conditioned reinforcement, choice, and the psychological distance to reward. In D. P. Hendry (Ed.), *Conditioned reinforcement* (pp. 163-191). Homewood, IL: Dorsey Press.
- Fantino, E., & Davison, M. (1983). Choice: Some quantitative relations. *Journal of the Experimental Analysis of Behavior*, **40**, 1-13.
- Fantino, E., Squires, N., Delbrück, N., & Peterson, C. (1972). Choice behavior and the accessibility of the reinforcer. *Journal of the Experimental Analysis of Behavior*, **18**, 35-43.
- Gibbon, J., Baldock, M. D., Locurto, C., Gold, L., & Terrace, H. S. (1977). Trial and intertrial durations in autoshaping. *Journal of Experimental Psychology: Animal Behavior Processes*, **3**, 264-284.
- Gibbon, J., & Balsam, P. (1981). Spreading association in time. In C. M. Locurto, H. S. Terrace, & J. Gibbon (Eds.), *Autoshaping and conditioning theory* (pp. 219-253). New York: Academic Press.
- Herrnstein, R. J. (1964). Secondary reinforcement and rate of primary reinforcement. *Journal of the Experimental Analysis of Behavior*, **7**, 27-36.
- Killeen, P. R. (1982). Incentive theory: II. Models for choice. *Journal of the Experimental Analysis of Behavior*, **38**, 217-232.
- Killeen, P. R., & Fantino, E. (1990). Unification of models for choice between delayed reinforcers. *Journal of the Experimental Analysis of Behavior*, **53**, 189-200.
- Luco, J. E. (1990). Matching, delay-reduction, and maximizing models for choice in concurrent-chains schedules. *Journal of the Experimental Analysis of Behavior*, **54**, 53-67.
- Mackintosh, N. J. (1974). *The psychology of animal learning*. London: Academic Press.
- Rescorla, R. A., & Wagner, A. R. (1972). A theory of Pavlovian conditioning: Variations in the effectiveness of reinforcement and nonreinforcement. In A. H. Black & W. F. Prokasy (Eds.), *Classical conditioning II: Current research and theory* (pp. 64-99). New York: Appleton-Century-Crofts.
- Ricci, J. A. (1973). Key pecking under response-independent food presentation after long simple and compound stimuli. *Journal of the Experimental Analysis of Behavior*, **19**, 509-516.
- Skinner, B. F. (1938). *The behavior of organisms*. New York: Appleton-Century.
- Squires, N., & Fantino, E. (1971). A model of choice in simple concurrent and concurrent-chains schedules. *Journal of the Experimental Analysis of Behavior*, **15**, 27-38.
- Terrace, H. S., Gibbon, J., Farrell, L., & Baldock, M. D. (1975). Temporal factors influencing the acquisition and maintenance of an autoshaped keypeck. *Animal Learning & Behavior*, **3**, 53-62.
- Vaughan, W., Jr. (1982). Choice and the Rescorla-Wagner model. In M. L. Commons, R. J. Herrnstein, & H. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 2. Matching and maximizing accounts* (pp. 263-279). Cambridge, MA: Ballinger.
- Vaughan, W., Jr. (1985). Choice: A local analysis. *Journal of the Experimental Analysis of Behavior*, **43**, 383-405.
- Williams, B. A. (1988). Reinforcement, choice, and response strength. In R. C. Atkinson, R. J. Herrnstein, G. Lindzey, & R. D. Luce (Eds.), *Stevens' handbook of experimental psychology: Vol. 2. Learning and cognition* (2nd ed., pp. 167-244). New York: Wiley.

Received February 26, 1990
Final acceptance October 6, 1990

APPENDIX 1

VAUGHAN'S (1985) RATIO MODEL

According to Vaughan (1985), the proportion of responses spent on the left initial link key is

$$\frac{B_L}{B_L + B_R} = \frac{r_L r_R (V_{2L} - V_{2R}) + ar_L V_{2L}}{a(r_L V_{2L} + r_R V_{2R})}.$$

Therefore,

$$\frac{B_L}{B_R} = \frac{\frac{r_L r_R (V_{2L} - V_{2R}) + ar_L V_{2L}}{a(r_L V_{2L} + r_R V_{2R})}}{1 - \frac{r_L r_R (V_{2L} - V_{2R}) + ar_L V_{2L}}{a(r_L V_{2L} + r_R V_{2R})}}.$$

Cross multiplying in the denominator,

$$\frac{B_L}{B_R} = \frac{\frac{r_L r_R (V_{2L} - V_{2R}) + ar_L V_{2L}}{a(r_L V_{2L} + r_R V_{2R})}}{\frac{a(r_L V_{2L} + r_R V_{2R})}{a(r_L V_{2L} + r_R V_{2R})} - \frac{r_L r_R (V_{2L} - V_{2R}) + ar_L V_{2L}}{a(r_L V_{2L} + r_R V_{2R})}}.$$

Multiplying denominator and numerator by $a(r_L V_{2L} + r_R V_{2R})$,

$$\frac{B_L}{B_R} = \frac{r_L r_R (V_{2L} - V_{2R}) + ar_L V_{2L}}{ar_L V_{2L} + ar_R V_{2R} - r_L r_R (V_{2L} - V_{2R}) - ar_L V_{2L}}.$$

Or,

$$\frac{B_L}{B_R} = \frac{r_L r_R (V_{2L} - V_{2R}) + ar_L V_{2L}}{ar_R V_{2R} + r_L r_R (V_{2R} - V_{2L})}.$$

Dividing through by $r_L r_R$ and then replacing r_i by $\frac{1}{t_{1i}}$,

$$\frac{B_L}{B_R} = \frac{V_{2L} - V_{2R} + a \frac{V_{2L}}{r_R}}{a \frac{V_{2R}}{r_L} + V_{2R} - V_{2L}} = \frac{V_{2L} - V_{2R} + at_{1R} V_{2L}}{V_{2R} - V_{2L} + at_{1L} V_{2R}}.$$

APPENDIX 2

MELIORATION APPROXIMATION TO DELAY REDUCTION

According to Vaughan (1985), the ratio of left and right initial-link responses (from Appendix 1) is

$$\frac{B_L}{B_R} = \frac{V_{2L} - V_{2R} + at_{1R}V_{2L}}{V_{2R} - V_{2L} + at_{1L}V_{2R}}.$$

Multiplying each term by $(t_{1L} \cdot t_{1R})$,

$$\frac{B_L}{B_R} = \frac{aV_{2L}t_{1L}t_{1R} + t_{1L}t_{1R}V_{2L} - t_{1L}t_{1R}V_{2R}}{aV_{2R}t_{1L}t_{1R} + t_{1R}t_{1L}V_{2R} - t_{1R}t_{1L}V_{2L}}.$$

Factoring out (t_{1R}/t_{1L}) , and adding 0 (right two terms) to the numerator and denominator,

$$\frac{B_L}{B_R} = \frac{t_{1R}}{t_{1L}} \cdot \frac{aV_{2L}t_{1L}t_{1R} + t_{1L}V_{2L} - t_{1L}V_{2R} + t_{1R}V_{2R} - t_{1R}V_{2R}}{aV_{2R}t_{1L}t_{1R} + t_{1R}V_{2R} - t_{1R}V_{2L} + t_{1L}V_{2L} - t_{1L}V_{2L}}.$$

Dividing the numerator and the denominator by $(t_{1L} + t_{1R})$ gives

$$\frac{B_L}{B_R} = \frac{t_{1R}}{t_{1L}} \cdot \frac{\frac{aV_{2L}t_{1L}t_{1R} + t_{1L}V_{2L} + t_{1R}V_{2R}}{t_{1L} + t_{1R}} - \frac{t_{1L}V_{2R} + t_{1R}V_{2R}}{t_{1L} + t_{1R}}}{\frac{aV_{2R}t_{1L}t_{1R} + t_{1L}V_{2L} + t_{1R}V_{2R}}{t_{1L} + t_{1R}} - \frac{t_{1L}V_{2L} + t_{1R}V_{2L}}{t_{1L} + t_{1R}}}.$$

Simplifying,

$$\frac{B_L}{B_R} = \frac{t_{1R}}{t_{1L}} \cdot \frac{\frac{aV_{2L}t_{1L}t_{1R} + t_{1L}V_{2L} + t_{1R}V_{2R}}{t_{1L} + t_{1R}} - V_{2R}}{\frac{aV_{2R}t_{1L}t_{1R} + t_{1L}V_{2L} + t_{1R}V_{2R}}{t_{1L} + t_{1R}} - V_{2L}}.$$

Substituting T_L and T_R , this is equal to Equation 6:

$$\frac{B_L}{B_R} = \frac{\frac{1}{t_{1R}} \cdot \frac{T_L - V_{2R}}{1}}{\frac{1}{t_{1R}} \cdot \frac{T_R - V_{2L}}{1}},$$

where

$$T_i = \frac{aV_{2i}t_{1L}t_{1R} + t_{1L}V_{2L} + t_{1R}V_{2R}}{t_{1L} + t_{1R}}$$

or

$$T_i = aV_{2i} \cdot \frac{1}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} + \frac{\frac{1}{t_{1R}}}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} \cdot V_{2L} + \frac{\frac{1}{t_{1L}}}{\frac{1}{t_{1L}} + \frac{1}{t_{1R}}} \cdot V_{2R}.$$